THE EVOLUTIONARY STATUS OF SS433

Andrew R. King[1,2], Ronald E Taam[1,3], Mitchell C. Begelman[1,4]

[1]Institute for Theoretical Physics, University of California at Santa Barbara, CA 93106-4030, U.S.A.

[2]Astronomy Group, University of Leicester, Leicester LE1 7RH, U.K.

[3]Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208

[4]JILA, University of Colorado, Boulder, CO 80309-0440, U.S.A.

ABSTRACT

We consider possible evolutionary models for SS 433. We assume that common–envelope evolution is avoided if radiation pressure is able to expel most of a super–Eddington accretion flow from a region smaller than the accretor's Roche lobe. This condition is satisfied, at least initially, for largely radiative donors with masses in the range $4M_\odot - 12M_\odot$. For donors more massive than about $5M_\odot$, moderate mass ratios $q = M_2/M_1 \gtrsim 1$ are indicated, thus tending to favor black–hole accretors. For lower mass donors, evolutionary considerations do not distinguish between a neutron star or black hole accretor. In all cases the mass transfer (and mass loss) rates $\dot{M}_{\rm tr} \sim 7 \times 10^{-6} - 4 \times 10^{-4}$ $M_\odot$ yr^{-1} are much larger than the likely mass–loss rate $\dot{M}_{\rm jet} \sim 10^{-6}$ $M_\odot$ yr^{-1} in the precessing jets. Almost all of the transferred mass is expelled at radii considerably larger than the jet acceleration region, producing the 'stationary' Hα line, the infrared luminosity, and accounting for the low X–ray luminosity.

Subject headings: accretion, accretion disks — binaries: close — X-rays: stars — stars: individual (SS 433)

1. INTRODUCTION

The nature of the unusual binary system SS 433 has been an interesting question ever since the recognition (Abell & Margon, 1979; Milgrom, 1979; Fabian & Rees, 1979) that the system drives precessing jets with velocities $\simeq 0.26c$. In particular, although the binary period $P = 13.1$ d has long been known (Crampton & Hutchings, 1981), there is no consensus about the component masses since all radial–velocity studies have to use emission lines, and one cannot be sure that the measured velocities are those of either star. The heavy extinction towards the object makes estimates of the companion's spectral type and luminosity difficult; dereddening with the usual values $A_V \simeq 7$ based on comparison of infrared and Hα intensities (e.g. Giles et al., 1979) suggests the presence of a Rayleigh–Jeans continuum in the optical, and thus possibly an early–type companion. Estimating the mass ratio from the duration of the observed X–ray eclipse (Kawai et al., 1989) is also difficult, as we know that the X–rays come from the moving jets (Watson et al., 1986) and may therefore be extended. The assumptions that the jets are partly obscured by the accretion disc and by the companion during eclipse lead (D'Odorico et al., 1991) to estimates $q = M_2/M_1 \sim 4$, where M_2, M_1 are the masses of the companion and compact star respectively, consistent with the presence of an early–type companion.

Observational hints that SS 433's companion is relatively massive ($q \gtrsim 1$) have, until recently, presented a dilemma to theorists. A large mass ratio would put SS 433 in a state often invoked in binary evolution scenarios. This situation tends to lead to high mass transfer rates, with a large fraction of the donor's mass being transferred on its thermal timescale if its envelope is predominantly radiative, and even more rapidly if the envelope is convective. The resulting short mass transfer lifetime for a fairly massive donor (i.e., $q \gtrsim 1$) offers a simple explanation for the uniqueness of SS 433. Furthermore, a high mass transfer rate is indicated by the mass loss rate $\dot{M}_{\rm jet} \sim 10^{-6}$ M$_\odot$ yr^{-1} in the precessing

jets (Begelman et al., 1980). However, this is also a potential problem: if the companion is indeed relatively massive, even thermal–timescale mass transfer leads to rates far in excess of the Eddington limit for an accretor of a few $M_\odot$, in excess even of the inferred mass-loss rates in the jets. Conventional wisdom has until recently suggested that such rates inevitably lead very quickly to common–envelope (CE) evolution, in which the compact object can neither accrete nor expel the transferred matter rapidly enough to prevent the formation of an envelope around the entire system. This would then probably appear as a giant, and certainly not be recognizable as an accreting binary. Since SS 433 is not yet in such a state, the predicted lifetime for its current state would become embarassingly short, requiring very high space densities of similar systems.

The problem is only slightly eased by abandoning the assumption $q \gtrsim 1$, since the mean density of the companion is essentially fixed by the requirement that it should fill its Roche lobe in a binary with a period of 13.1 d (mass transfer through stellar wind capture is very unlikely to give the high mass transfer rates inferred). A companion star in the process of crossing the Hertzsprung gap is the only likely possibility, as a main–sequence companion would have to be improbably massive (see eqs 4, 5 below) while nuclear–timescale mass transfer from a giant companion would give far too low a transfer rate. This then leads back to mass transfer on something like the thermal time of the expanding companion star; while this is somewhat milder than in the case $q \gtrsim 1$, it would still be well above the values hitherto thought likely to produce a common envelope.

Recent work on the neutron–star X–ray binary Cygnus X–2 (King & Ritter, 1999; Podsiadlowski & Rappaport, 1999) offers a way out of this dilemma: it is evident that this system has survived an episode of thermal–timescale mass transfer resulting from an initial mass ratio $q_i \gtrsim 1$ without entering CE evolution. The aim of this paper is to investigate whether this is possible in SS 433 also, and thus to discover its likely evolutionary status.

2. AVOIDANCE OF COMMON ENVELOPE EVOLUTION

King & Ritter (1999) show that the progenitor of Cygnus X–2 must have transferred a mass $\sim 3M_\odot$ at rates $\dot{M}_{\rm tr} \gtrsim 10^{-6}$ $M_\odot$ yr^{-1} (the Case AB evolution suggested by Podsiadlowski & Rappaport, 1999 leads to a similar requirement). This greatly exceeds the Eddington rate $\dot{M}_{\rm Edd} = L_{\rm Edd}/c^2$ for a 1.4$M_\odot$ neutron star. This star evidently accreted only a tiny fraction of the transferred mass, expelling the rest from the system entirely. The obvious agent for this is radiation pressure. King & Begelman (1999) (hereafter KB99) suggest that expulsion occurs from the 'trapping' radius

$$R_{\rm ex} \sim \left(\frac{\dot{M}_{\rm tr}}{\dot{M}_{\rm Edd}}\right) R_S \simeq 1.3 \times 10^{14} \dot{m}_{\rm tr} \text{ cm}, \tag{1}$$

where R_S is the Schwarzschild radius and $\dot{m}_{\rm tr}$ is the transfer rate expressed in $M_\odot$ yr^{-1}. (Note that $R_{\rm ex}$ is independent of M_1 since both $\dot{M}_{\rm Edd}$ and R_S scale as M_1.) Within this radius advection drags photons inward, overcoming their outward diffusion through the matter. If the matter has even a small amount of angular momentum most of it is likely to be blown away as a strong wind from $R_{\rm ex}$: the gravitational energy released by accretion at $\sim \dot{M}_{\rm Edd}$ deep in the potential of the compact star is used to expel the remainder $(\sim \dot{M}_{\rm tr} \gg \dot{M}_{\rm Edd})$ of the infall, which is only weakly bound at distances $\sim R_{\rm ex}$ (cf Blandford & Begelman 1999). KB99 suggest that CE evolution is avoided provided that $R_{\rm ex}$ is smaller than the accretor's Roche lobe radius R_1. If the accretor is the less massive star this is given approximately by

$$R_1 = 1.3 \times 10^{11} m_1^{1/3} P_{\rm d}^{2/3} \text{ cm}, \tag{2}$$

where $m_1 = M_1/M_\odot$ and $P_{\rm d}$ is the binary period in days. Since this is related to the Roche lobe radius R_2 of the companion star via

$$\frac{R_2}{R_1} \simeq \left(\frac{M_2}{M_1}\right)^{0.45}, \tag{3}$$

(cf King et al., 1997) KB99 were able to determine whether Roche–lobe overflow from various types of companion star would lead to CE evolution or not. They concluded that

CE evolution was unlikely for mass transfer from any main–sequence or Hertzsprung gap star with $q \gtrsim 1$ provided that its envelope was largely radiative. In the next section we investigate possible companion stars in SS 433.

3.   THE EVOLUTION OF SS 433

If the companion star in SS 433 is more massive than the compact accretor $(q > 1)$ and fills its Roche lobe, then from (2) and (3) it has radius

$$R_2 = 10 \mathrm{R}_\odot m_1^{-0.12} m_2^{0.45} \left(\frac{P_\mathrm{d}}{13.1} \right)^{2/3}. \tag{4}$$

In the opposite case $(q \lesssim 1)$ we have instead

$$R_2 = 10 \mathrm{R}_\odot m_2^{0.33} \left(\frac{P_\mathrm{d}}{13.1} \right)^{2/3}. \tag{5}$$

In either case this is obviously a fairly extended star, and clearly well above the upper main sequence mass–radius relation for any realistic mass $M_2 = m_2 \mathrm{M}_\odot$. By the reasoning of the previous section, the only possible companions are stars which came into contact with the Roche lobe as they crossed the Hertzsprung gap. Since such stars are by definition out of thermal equilibrium, we cannot assume that their structure is given by that of a single star of the same instantaneous mass (although this is approximately true for companions of modest mass $m_2 \lesssim 3.5$ with $q \lesssim 1$; Kolb, 1998). Instead we must follow their evolution under mass loss explicitly.

The lack of clear dynamical mass information means that there is considerable freedom in trying to fit the current state of SS 433, and one cannot expect to find a unique assignment. We restricted the evolutions we considered to those satisfying the following list of conditions at the current epoch:

1. $P_d \simeq 13.1$

2. Mass transfer rate $\dot{M}_{\rm tr} > \dot{M}_{\rm jet} \sim 10^{-6}$ $M_\odot$ yr^{-1}

3. $R_{\rm ex} < R_1$

4. The companion does not have a deep convective envelope (which would make CE evolution inevitable). In practice this means that the stellar effective temperature should typically exceed a value ~ 6000 K which in turn requires an initial companion mass $M_{2i} \gtrsim 4M_\odot$

5. The time since mass transfer exceeded the Eddington limit is $t_0 \sim 10^3$ yr.

Condition 5 comes from observations of the surrounding W50 nebula. If this is attributed to interaction with the jets one finds $t_0 \sim 10^3$ yr, assuming that the jets were produced promptly (Begelman et al., 1980; Königl, 1983). We calculated evolutionary models satisfying these conditions using the code developed by Eggleton (1971, 1972), with the Roche lobe radius given (more accurately than 4, 5 above) by

$$\frac{R_2}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}, \tag{6}$$

with a the binary separation and a mass transfer formulation as described in Ritter (1983). In all cases the mass transfer rate is highly super–Eddington; we assume that the transferred mass is lost from the binary with the specific angular momentum of the compact accretor. From eq. 5 of King & Ritter (1999) it is easy to show that the orbital period decreases for mass ratios $q > q_{\rm crit} \simeq 1.39$, and increases for smaller q. Because higher mass stars drive higher rates of mass transfer, the companion star mass is limited to $\lesssim 12M_\odot$ for otherwise birth rate requirements for systems similar to SS 433 would become severe (see below). Table 1 shows our results for systems characterized by an initial orbital period of 13.1 d.

4. DISCUSSION

Table 1 provides only a coarse sampling of the parameter space of possible evolutionary models for SS 433. However we can already make some interesting statements.

For a given initial mass *ratio* $q_i = M_{2i}/M_1$, (e.g. sequences 2 and 4) higher masses imply higher mass loss rates, and hence that more mass is lost after a given time ($\sim 10^3$ yr). We can understand this as a consequence of the shorter thermal timescale for higher–mass stars. The orbital period decrease is greater for higher masses as a result. (Note that sequence 1 has q_i very close to q_{crit}.) For a given initial companion mass M_{2i} (compare sequences 1 - 3) decreasing the compact object mass produces the same trends, because it amounts to increasing the mass ratio further above q_{crit}. For a neutron–star accretor (sequence 5) the larger mass ratio wins out over the smaller companion mass, again producing the same trends. This implies that a neutron–star accretor provides a good fit to the present state of SS 433 only if the companion has quite a low mass ($\sim 4 - 5 M_\odot$) in a fairly narrow range: masses much lower than this imply large convective mass fractions at or soon after the start of mass transfer, and thus CE evolution. This results in a dynamical instability or a delayed dynamical instability as discussed by Webbink (1977), Hjellming & Webbink (1987), and Hjellming (1989). For companion stars more massive than about $5 M_\odot$ with a neutron star companion, binary evolution leads to a decrease of the orbital separation and period even after 1000 yrs, excluding such systems as candidate progenitor systems for SS 433. For longer initial periods, the companion is likely to have a convective envelope at the onset of mass transfer, and thus enter a CE stage.

Depending on the component masses, mass transfer rates $\dot{M}_{tr} \sim 7 \times 10^{-6} - 4 \times 10^{-4}$ $M_\odot$ yr^{-1} are typical for a system with a period of 13.1 d, and can evidently be ejected without causing the onset of CE evolution provided that the companion is predominantly radiative. The resulting mass transfer lifetimes are in the range $10^4 - 10^5$ yr, given largely by the

thermal timescale of the companion. They cannot be much greater than this, since this requires companion masses $\lesssim 4 M_\odot$, which are subject to a dynamical instability. The birthrate requirement for systems like SS 433 is thus of order $10^{-4} - 10^{-5}$ yr^{-1} in the Galaxy.

The predicted mass transfer rates $\dot{M}_{\rm tr} \sim 7 \times 10^{-6} - 4 \times 10^{-4}$ M$_\odot$ yr^{-1} are in all cases much larger than the likely mass–loss rate $\dot{M}_{\rm jet} \sim 10^{-6}$ M$_\odot$ yr^{-1} in the precessing jets (Begelman et al., 1980). We expect that the jets are ejected from a region no larger than $R_{\rm jet} \sim (\dot{M}_{\rm jet}/\dot{M}_{\rm tr})R_{\rm ex} \sim 1 \times 10^8$ cm; their quasi-relativistic velocity suggests that they emerge from a smaller radius, i.e., a few times the neutron–star radius 10^6 cm or the black–hole Schwarzschild radius $3 \times 10^5 m_1$ cm. The jets constitute just the innermost part of the mass expulsion from the accretion flow: almost all of the transferred mass is lost from larger radii, $\gtrsim R_{\rm ex}$. In addition to accounting for the very low observed X–ray luminosity (which probably comes entirely from the jets), this expulsion of matter is presumably the source of the 'stationary' Hα line and the associated free–free continuum seen in the near infrared (Giles et al., 1979). The emission measure $V N_e^2 \simeq 10^{61}$ cm^{-3} of the latter is consistent with this, as the likely radius $R \sim 10^{15}$ cm of this region (Begelman et al., 1980) implies $N_e \sim 10^8$ cm^{-3}, and thus outflow rates as high as

$$\dot{M}_{\rm out} \simeq 4\pi R^2 v N_e m_H \sim 2.8 \times 10^{-3} \text{ M}_\odot \text{yr}^{-1}, \tag{7}$$

where $v \sim 1000$ km s^{-1} is the velocity width of the Hα line.

The very high mass transfer rates encountered in these calculations make it difficult to follow them to their natural endpoints, as assumptions such as synchronous rotation of the donor begin to break down. However the main outlines of the future evolution of systems are fairly clear, provided that the system does not enter a CE phase as a result of a delayed transition from thermal to dynamical timescale mass transfer. (This delayed dynamical instability is avoided in higher mass systems with mass ratio close to unity, again tending

to favor black–hole systems. Sequence 5 is likely to encounter this instability, cf King & Ritter, 1999). An initial mass ratio $q \gtrsim 1$ implies that the Roche lobe will shrink before the mass ratio reverses, and thus that the current mass transfer phase is likely to end with a fairly tight system consisting of the black hole or neutron star accretor (mass effectively unchanged) and the helium core of the donor (cf King & Ritter, 1999). For $M_2 < 12 M_\odot$ at the onset of mass transfer the core has mass $M_{\mathrm{He}} \sim 2 M_\odot$. This star will re–expand through helium shell–burning, and will probably initiate a further short mass transfer phase (so–called Case BB; Delgado & Thomas, 1981; Law & Ritter, 1983), depending on the binary separation. The donor will end its life as a CO white dwarf. The binary may be tight enough for coalescence to occur because of gravitational radiation losses within 10^{10} yr. Systems of this type would therefore be good candidates for gamma–ray burst sources, although detailed evolutionary calculations to check the scenario sketched here are clearly required before we can make this statement with any confidence. In particular, it would be premature to translate the predicted birthrates $10^{-4} - 10^{-5}$ yr^{-1} into a predicted gamma–ray burst rate.

REFERENCES

Abell, G.O, Margon, B., 1979, Nat. 279, 701

Begelman, M.C., Sarazin, C.L., Hatchett, S.P., McKee, C.F., Arons, J., 1980, ApJ, 238, 722

Blandford, R. D., Begelman, M. C. 1999, MNRAS, 303, L1 (BB99)

Crampton, D., Hutchings, J.B., 1981, ApJ, 251, 604

Delgado, A.J., Thomas, H.C., 1981, A&A, 96, 142

D'Odorico, S., Oosterloo, T., Zwitter, T., Calvani, M., 1991, Nat., 353, 329

Eggleton, P.P. 1971, MNRAS, 151, 351

Eggleton, P.P. 1972, MNRAS, 156, 361

Fabian, A.C., Rees, M.J., 1979, MNRAS, 187, 13

Giles, B.A., King, A.R., Cooke, B.A., McHardy, I.M., Lawrence, A., 1979, Nat. 281, 282

Hjellming, M.S., 1989, PhD thesis, University of Illinois

Hjellming, M.S., Webbink, R.F. 1987, ApJ, 318, 794

Kawai, N., Matsuoka, M., Pan, H.C., Stewart, G.C., 1989, PASJ 49, 491

King, A.R., Begelman, M.C, 1999, ApJ, 519, L169 (KB99)

King, A.R., Frank, J., Kolb, U., Ritter, H., 1997, ApJ, 484, 844

King, A.R., Ritter, H., 1999, MNRAS, 309, 253

Kolb, U., 1998, MNRAS, 297, 419

Königl, A. 1983, MNRAS, 205,471

Law, W.Y., Ritter, H., 1983, A&A, 123, 33

Milgrom, M., 1979, A&A 76, L3

Podsiadlowski, Ph., Rappaport, S.A., 1999, preprint astro-ph 990648

Ritter, H. 1983, A&A, 202, 93

Watson, M.G., Stewart, G.C., Brinkmann, W., King, A.R. 1986, MNRAS 222, 261

Webbink, R.F., 1977, ApJ 211, 486

Table 1:

Possible Evolutionary Sequences for SS 433

Sequence	t_0 (yr)	M_1 (M$_\odot$)	M_{2i} (M$_\odot$)	M_2 (M$_\odot$)	$\dot{M}_{\mathrm{tr}}$ (M$_\odot$ yr^{-1})	P (d)
1	1007	6	8	7.990	2.3×10^{-5}	13.09
2	1003	4	8	7.987	3.3×10^{-5}	13.05
3	984	2	8	7.957	1.8×10^{-4}	12.59
4	1004	6	12	11.879	3.3×10^{-4}	12.88
5	1008	1.4	5	4.996	6.7×10^{-6}	13.03